Estimating Tropical Cyclone Central Pressures for Reanalysis of Global Fields

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Submitted to *Monthly Weather Review*
October 2011

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Abstract

Sparse surface pressure observations, even in the absence of other observation types, can be used in advanced data assimilation systems to generate global retrospective weather analyses (i.e., global "reanalyses"). Such sparse-input reanalyses spanning a century or longer are now being produced. To provide additional data for one such effort, the 20th Century Reanalysis Project (20CR), minimum central pressures for tropical cyclones (TCs) were estimated from wind speeds contained in the National Climatic Data Center's International Best Track Archive for Climatic Stewardship (IBTrACS) and then assimilated into 20CR. This prior research resulted in improvements to the representation of TCs in the 20CR fields. Here, two empirical TC wind speed/pressure relationships are evaluated in advance of subsequent global reanalyses. One is based on the gradient wind equation used for 20CR; the other is based on the cyclostrophic balance equation. Both methods are similar in their effectiveness. A potential concern arising from Dvorak-based TC intensity estimates in IBTrACS has been investigated. Random errors are underestimated when wind speed/pressure relationships are developed from Dvorak-influenced data, but biases are found to be small. The additional pressure values obtained through a wind speed/pressure relationship and information about their associated errors may be useful for further improving the assimilation of tropical cyclones in historical reanalyses of global fields. Despite a slightly larger expected error, we recommend the use of more physically based gradient wind equation relationships for such historical reanalyses rather than the widely used relationships derived from cyclostrophic balance.

1. Introduction

The objective numerical combination of historical observations using data assimilation is commonly referred to as retrospective analysis or "reanalysis". Several such reanalysis datasets have been produced since the mid-1990s; most extend back only to the mid- to late-twentieth century and are based primarily on upper-air or satellite data. (See Compo et al. (2011) for a historical discussion). Recent studies have suggested that historical surface pressure observations have a broad application for determining the synoptic atmospheric circulation going back a century or more (Whitaker et al. 2004, Anderson et al. 2005, Compo et al. 2006, Thépaut 2006, Whitaker et al. 2009). These studies have shown that even without incorporating other observation types, an advanced data assimilation system such as an Ensemble Kalman Filter or 4D-variational assimilation can combine surface pressure observations and numerical weather prediction (NWP) model-generated first guess fields to produce useful three-dimensional global atmospheric fields. Recently, a surface-pressure based reanalysis dataset called the 20th Century Reanalysis Project (20CR) has been generated. Its second version (20CRv2) spans the years 1871-2008 (Compo et al. 2011). The 20CR data set may be particularly suited for climate research compared to previous reanalyses because the assimilation of only surface pressure ameliorates artificial variability associated with frequent changes in the global observing system.

These global datasets should not be confused with a different kind of "reanalysis": the development of Tropical Cyclone (TC) best-track datasets such as HURDAT; the re-evaluation of records from national and regional specialized meteorological centers

(RSMC) and tropical cyclone warning centers; or the compilation of these data into large collections such as the International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al. 2010). These best-track data are often referred to as “reanalyses” of the original tropical cyclone intensity and position data obtained from marine, land, and satellite platforms. The ongoing revision to these datasets, such as being undertaken by the Atlantic hurricane database reanalysis project (Landsea et al. 2004), Southwest Pacific Enhanced Archive of Tropical Cyclones (Diamond et al. 2011), the University of Wisconsin-Madison/National Climatic Data Center record of hurricane intensity (Kossin et al. 2007), and the RSMC La Reunion/Australian effort for the South Indian Ocean (Levinson et al. 2010), are also referred to as “reanalyses”. To avoid confusion, we will refer to “global reanalyses” when discussing global atmospheric fields produced through data assimilation.

One connection between the two “reanalyses” is that the global reanalysis datasets often have had a poor representation of TCs, though this has been improving (Hart et al. 2008), thanks in part to the increased amount of TC data in recent decades. In particular, Hart et al. (2008) found that information about the size and the location of TCs has more influence on the quality of a global reanalysis than does information about TC intensity. Improving the representation of intensity may require a different approach than is used in many of the existing global reanalysis datasets, which rely heavily on ship and station observations that happen to be close to TCs. Towards this end, the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis employed a storm relocation technique (Liu et al. 1999) to “move” vortices to the estimated location before the data assimilation system combined other observations (Saha et al. 2010). The

Japan Reanalysis 25 (Onogi et al. 2007) assimilated synthetic wind profiles (Fiorino 2002) to improve the representation of TCs. Both of these efforts improved many of the characteristics of TCs in the global reanalysis fields compared to earlier datasets (Schenkel and Hart 2011).

For a global reanalysis, direct assimilation of TC central pressure values might be one way to bring about further improvement, particularly in the 20CR system, which assimilates only surface and sea level pressure reports. This is impeded, however, by the scant pressure data in the best-track data sets. For example, an analysis of the records in IBTrACS shows that before the 1950s few TC records contain both wind and pressure values. Even in the last decade, more than 400 TC records (out of a total of about 25 000) have only wind speed. Thus, to reanalyze earlier decades it will be necessary to estimate central pressure values from wind speeds. Fortunately, in the absence of more direct estimates of tropical storm central pressure, the tropical storms community has long used wind speed/pressure relationships to estimate central pressure from wind speed (e.g., Dvorak 1975; Holland 1980; Love and Murphy 1985; Knaff and Zehr 2007; Holland 2008; Holland et al. 2010, Courtney and Knaff 2009).

Several algorithms or conceptual models exist to estimate central pressure from TC wind speed. Most empirical wind speed/pressure models are based on a modified form of the cyclostrophic balance equation (hereafter CBE, e.g., Fujita 1971; Atkinson and Holliday 1977; Harper 2002), which requires only an estimate of the wind speed and some empirical parameters appropriate for a particular region or basin. This property is commonly referred as ‘single wind speed pressure relationship’ (Harper 2002). For the sake of brevity, we will use the term ‘univariate’ to refer to this property for the reminder of the paper. Most TC estimates in best-track datasets have been aided by some form of univariate empirical method (Knaff 2010). Indeed, five different variants have been used in TC operational centers throughout the world (Knaff and Zehr 2007). The CBE is an integral part of the Dvorak (1975) satellite cloud image analysis technique, which is used to arrive at simultaneous wind speed and pressure estimates (Velden et al. 2006).

The CBE as used for TC wind-to-pressure relationships can be expressed as

$$V = c\left(P_{ref} - P_c\right)^k \tag{1}$$

where V is the maximum wind speed, P_{ref} is the reference or environmental pressure, P_c is the minimum central pressure of the cyclone, and c and k are empirical parameters with k between 0 and 1. When k = 0.5, the dynamical cyclostrophic balance equation is recovered (Holton 1992). For application to TCs, the parameters c and k differ from one basin to another. An example of the CBE for the Atlantic basin is given by

$$V = 8.354\left(1015.8 - P_c\right)^{0.6143} \tag{2}$$

where V is the cyclone's maximum 1-minute mean wind speed in units of knots[2] and P_c is in hPa (Brown et al. 2006).

More complex algorithms have also been developed. Recently, many operational applications have employed the Knaff and Zehr (2007) and Courtney and Knaff (2009) algorithm (hereafter KZ07 and CK09 respectively), which uses wind speed and several additional environmental factors to determine central pressure. It has the general form of a second-order polynomial approximating the gradient wind. Another algorithm is that of Holland (2008) and Holland et al. (2010) (hereafter H08, HBF10). In addition to providing central pressure from wind speed, it also generates several additional storm and

[2] The equation can be rewritten for V in m s^{-1} as $V = 4.298\left(1015.8 - P_c\right)^{0.6143}$.

environmental factors. The H08 and HBF10 algorithms are successors to that of Holland (1980), the first theoretically-based gradient wind model.

Both the KZ07 and HBF10 multivariate algorithms pose significant challenges if they are to be used for historical data assimilation. KZ07 incorporates environmental pressure and wind field information in 6-hourly intervals from the NCEP-NCAR reanalysis dataset (Kalnay et al. 1996). Using estimated central pressure values that include existing global reanalysis input might introduce a covariance between the errors in the individual values. It may also propagate biases from the utilized reanalysis fields to any future assimilation effort. Additionally, as noted by KZ07, the algorithm is only intended to be applied in the time range of the NCEP-NCAR reanalysis dataset, 1948-present.

In contrast, the HBF10 updated algorithm appears to be applicable generally to the full time range of historical TC data because it does not incorporate global reanalysis or analysis fields. However, complex models such H08 and HBF10 (or KZ07 and CK09) require multiple input variables. The uncertainty associated with these variables, such as sea surface temperature, storm motion or storm size may be large in the 19th and early 20th centuries. These large uncertainties will propagate to the uncertainty in the estimated central pressure and cause that uncertainty to co-vary with the inputs. A data assimilation system such as used in 20CR would give little weight to pressure values with large uncertainties.

Rather than employing a multivariate wind/pressure relationship that may contain complicated and possibly co-varying uncertainties, when an IBTrACS TC report contained only wind values the 20CRv2 assimilated TC central pressure estimates generated from a simple approximation to the gradient wind equation (GWE). Like the dynamical cyclostrophic balance equation, the full gradient wind equation also has pressure dependent on squared wind speed. This relationship can be cast as a second order polynomial. Such an approach simplifies that of KZ07, who incorporated latitude dependence and several other factors, including storm movement.

For this simpler GWE model, consider the gradient wind equation in coordinates relative to the horizontal flow (Holton 1992):

$$\frac{V^2}{R} + fV = -\frac{1}{\rho}\frac{\partial P}{\partial n} \tag{3}$$

where R is the radius of curvature, f is the Coriolis parameter, P and ρ are the air pressure and density, respectively, and n is in the direction normal to the horizontal velocity. Approximating $-\frac{\partial P}{\partial n} = \frac{\Delta P}{\Delta n} = \frac{P_{ref} - P_c}{R}$ and collecting terms, we can express P_c as:

$$P_c = P_{ref} - \alpha V - \beta V^2 \tag{4}$$

where P_{ref}, α, and β are coefficients that will be determined empirically; V is units of m s^{-1} and P_c is in hPa.

Preliminary unpublished studies conducted after the first 20CR suggested that the supplementary pressure values determined using the GWE (4) would have a beneficial impact on the 20CRv2 representation of TCs. Therefore, almost 65 000 TC central pressure estimates contained in early versions of IBTrACS or determined from IBTrACS wind values were assimilated into 20CRv2 (Compo et al. 2011). Figure 1 illustrates the impact of these estimated pressure values on the analyzed sea level pressure field during Hurricane Cleo, which became a hurricane on 12 August 1958 and reached Category 3 status on 14 August. This hurricane is a useful case study in part because in 1958 four different reanalysis datasets are available for comparison: 20CR version 1, 20CRv2, NCEP-NCAR (Kalnay et al. 1996), and ERA-40 (Uppala et al. 2005). IBTrACS does not contain a pressure estimate for Cleo until 14 August 18UTC. We have examined all maps during Cleo and find that 14 August 6UTC is representative of the positive impact of the GWE–based pressure values. The fact that 20CRv2, which included estimated TC pressures, shows a vortex (Fig. 1b) while 20CRv1 does not (Fig. 1a) attests to this positive impact. Perhaps more surprising is that the upper-air based reanalyses, NCEP-NCAR and ERA-40, show only a hint of a closed circulation despite the presence of a Category 3 hurricane (90 knot maximum sustained 1 minute mean winds according to HURDAT (Landsea et al. 2004)). Comparisons with other storms during 1958 (not shown) lead to similar conclusions on the efficacy of assimilating TC pressure estimates. A more extensive study examining mid-tropospheric thickness anomalies (Truchelut and Hart 2011) demonstrated that 20CRv2 has an improved signature of TCs compared to 20CRv1.

The purpose of this paper is to evaluate the methodology used to estimate TC central pressures for 20CRv2 from the late 19th century to the present, in preparation for future historical global reanalyses. Two univariate wind speed-to-pressure relationships are examined here: the GWE and the CBE. In each, parameters are determined empirically. The necessary observational data are described in Section 2. In Section 3, the CBE is compared to the GWE used in 20CRv2. Then, the GWE used in 20CRv2 is further investigated in terms of the quality and quantity of pressure values generated and their spatial distribution. Section 4 discusses potential improvements and issues, including the influence of satellite-based empirical techniques on best-track TC estimates, and revisits the CBE and GWE in the data-rich North Atlantic and West Pacific basins. Section 5 provides discussion, and conclusions are given in Section 6.

2. Data

Two different observational tropical cyclone datasets were used in this study. The first is the HURDAT dataset (Landsea et al. 2004), which was used to evaluate methods for 20CRv2. The HURDAT dataset is the official record of tropical storms and hurricanes in the Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea since 1851. Its time resolution is 6 hourly. Wind speeds are reported as peak 1-minute averages at an elevation of 10 meters above the surface.

Unfortunately, HURDAT is limited to the North Atlantic Ocean. To extend the pressure data available for global data assimilation into 20CRv2, the IBTrACS compilation was used (Kruk et al. 2009; Knapp et al. 2010). It is comprised of TC data from various agencies across the globe. If more than one data source is identified, an average of all available estimates is used for 20CRv2. The time resolution is 6 hourly. In the process of compiling IBTrACS, several adjustments were made to agency data, e.g., all maximum sustained wind estimates were normalized to be consistent with a 10-minute average[3], and all minimum central pressure estimates of all reported observations for each provided record were averaged. In 20CRv2, both minimum central pressure as reported in the available IBTrACS version (v01r01) and estimated central pressures determined from its wind speeds using a GWE were assimilated. For the additional evaluation described below, IBTrACS v03r01 is also used.

[3] In particular, HURDAT's peak 1-minute average wind speeds were normalized by a factor of 0.88 (Knapp et al. 2010).

IBTrACS v01r01 uses nine different non-overlapping sub-basins for delineating TC identity: EPCP (East Pacific/Central Pacific); EPEP (East Pacific); NA (North Atlantic); NI (North Indian); SI (South Indian); SIWA, (South Indian/West Australia); SPEA (South Pacific/East Australia); SPSP (South Pacific), and WP (West Pacific). This main-basin/sub-basin category scheme evolved into a more elaborate system in v03r01. For this study, we are keeping the simpler scheme of v01r01. Figure 2 orients the reader to the sub-basins using the locations of central pressure data during 2000 from v01r01.

The number of IBTrACS TC records (pressure and/or wind speed estimates) available in each basin is presented in Table 1 as a function of the record types in each basin: pressure only, wind only, or pressure and wind. The impact of aircraft and satellite data is seen very clearly when these TC record counts are presented in decadal bins (Fig. 3); the number of wind-only records per decade increases sharply in the 1950's and continues to rise through the 1990's.

3. Minimum central pressure estimates for the 20th Century Reanalysis Project (v2)

a. Errors of GWE estimates

Prior to the production of 20CRv2 we examined the performance of two models, CBE (2) and GWE (4), using HURDAT's Atlantic central pressure estimates from the 30-year period 1977-2006. The number of 6 hourly TC reports available is presented in Table 2 as a function of Saffir-Simpson category. For those HURDAT records having both pressure and wind speed estimates (P_c, V), the CBE (2) and GWE (4) models were applied and both bias (model estimate minus HURDAT estimate) and root-mean-square difference (RMS) statistics were computed.

To ensure that the GWE evaluation was independent of the period used in the parameter fitting, a three-year jackknifing procedure was used. In this, 3 years of data were excluded, e.g., 1977-1979, and the parameters were estimated using the remaining 1980-2006 (P_c, V) dataset. The resulting model is applied to the independent period and the evaluation statistics were accumulated. The three year window was then shifted to exclude 1980-1982, the GWE parameters recomputed using the remaining years, and the procedure repeated. For the CBE, the parameters of Brown et al. (2006) were applied, and no jackknifing was performed. Note that Brown et al. (2006) parameters were determined from a dataset limited to wind and pressure values from times within three hours of an aircraft reconnaissance measurement.

Figure 4 shows the bias and RMS statistics from these procedures. The two models yield very similar RMS statistics, although the GWE has the smallest magnitude bias for Categories 4 and 5 hurricanes (Fig. 4). Overall, the GWE is the least biased method, has the smallest RMS error for Category 5, and has comparable errors to the CBE for other categories.

Given the results shown in Fig. 4, we focused on the GWE and used wind and pressure data from IBTrACS to study the error characteristics of estimated pressure values in other basins. We calculated parameters of the GWE (4) separately for each of the nine sub-basins in Fig. 2. Note that these parameters, shown in Table 3, are valid for peak 10-minute average wind speeds. To ensure that the validation period could have no possible dependence on the fitting period, we determined the parameters using data spanning 1979 to 2007 and then verified against the independent period of 1958 to 1978. The year 1979 was chosen as an arbitrary cut-off to capture most of the satellite period. Data availability for 1958-1978 is presented in Table 4.

Results are presented in Fig. 5 as a function of tropical cyclone intensity using bins from the Saffir-Simpson scale. Use of the Saffir-Simpson scale for this purpose with 10 min averaged winds requires some justification, as the current National Hurricane Center policy is to use 1-minute average winds in assigning tropical storms to a particular Saffir-Simpson category (Franklin 2005). However, early presentations of the Saffir-Simpson scale were written in terms of velocities “in 2- or 3-second gusts” (Saffir 1975) or without any definition of velocity (Simpson 1974) and were sometimes accompanied by text discussing both wind gust velocities and “fastest-mile speeds” (Saffir 1973). There is also not a perfect match between speed criteria for each category, even when roundoff errors associated with unit conversion are taken into account. The overall sense is of a general, not precise, means of categorizing tropical cyclone strength. With that in mind, and since there is no single unified method of categorizing global TCs, we used the prevalent Saffir-Simpson boundaries (Table 2) to bin each basin’s (P_c, V) pairs before computing RMS errors, even though IBTrACS wind speeds are 10-minute averages. The results in Fig. 5 are shown only for categories that have more than 30 reports in a sub-basin. As in Fig. 4, errors generally increase with increasing intensity, although the North Atlantic errors are 1.5 to 2 times larger than in Fig. 4. The quality of the pressure and wind speed estimates in IBTrACS from 1958 to 1978 might be lower than in the more recent period, so the RMS statistics may contain a contribution from pressure or wind errors that are larger than seen in Fig. 4. When all TC categories are pooled (labeled

"Overall") the highest error value is about 15 hPa for the Central Pacific sub-basin (EPCP); the lowest is ~4 hPa for the East Australian sub-basin (SPEA).

b. Spatial distribution

The TC central pressure values estimated using the GWE (4) for 20CRv2 complement, both temporally and spatially, the extant central pressure data in IBTrACS. As an example of this supplementary nature, Fig. 6 shows their geographical distribution in the 1960s and 1990s compared to the existing pressure estimates available in IBTrACS. The most striking feature of this comparison is that 20CRv2 GWE-based pressure estimates for the 1960s (Fig. 6b) occur mostly in regions with few IBTrACS estimated TC central pressures (Fig. 6a): the Eastern Pacific, Central Pacific, South Pacific/East Australian, and South Indian basins. In the 1990s, both IBTrACS (Fig. 6c) and GWE-estimated (Fig. 6d) TC central pressures show similar distributions except in the North Atlantic, where most IBTrACS records already contain TC central pressure estimates.

4. Re-evaluation of wind speed/pressure relationship options

While the results of assimilating GWE-estimated TC pressures into the 20CRv2 are encouraging, we expect that improvements are possible for future global reanalyses. The evaluation of the CBE in Section 3 relied on pre-determined parameters from Brown et al. (2006). Calculating the CBE and GWE parameters from the same dataset may produce a different result than seen in Fig. 4. Additionally, the best-track datasets contain pressure estimates that are influenced by Dvorak or Dvorak-like satellite techniques (H08, CK09, Knaff 2010, HBF2010). The CBE and GWE parameters may change if estimates with Dvorak influences are excluded. Hence we have performed a careful re-evaluation of the decision to use a GWE model, and in the process assessed in some detail a few of the issues associated with fitting best-track data.

a. Best-track bias towards univariate models

As a first step in re-evaluating the GWE and CBE, we determine the parameters of both models using the same dataset, rather than employing the Brown et al. (2006) CBE parameters presented in (2). We choose to examine the relatively data-rich West Pacific and North Atlantic basins for this part of the study. Table 5[4] shows the CBE and GWE parameters for each basin as calculated from all available wind/pressure pairs (V, P_c) in IBTrACS during 1977 to 2006, the same period used for Fig. 4. The number of TC estimates available in each basin as a function of Saffir-Simpson category is listed in Table 6. Figure 7 illustrates the mean bias and the RMS error of the resulting GWE and CBE models for these sub-basins as a function of Saffir-Simpson category. As in Fig. 4, the three-year jackknife method was used as a means of cross-validation, but this time for both models. In the West Pacific, biases are generally within ±1 hPa, except for the category 4 GWE. RMS errors increase with increasing storm strength and decreasing sample size, but are always less than 8 hPa and nearly identical for both models. In the Atlantic, strikingly low bias values (± 1 hPa) for both models are evident across all categories.

However, these values for bias and RMS may be artificially low, as many studies have shown systematic biases in the operational TC pressure estimates that arise from the

[4] We note that the number of North Atlantic IBTrACS records for 1979-2007 shown in Table 3 exceeds the number for 1977-2006 by 113. At first it seems implausible that 2007 would have so many more records than 1977 and 1978 combined. However, the 1977 season was "rather inactive" (Lawrence 1978) and the 1978 season had far fewer hurricane hours than normal (Lawrence 1979), while in 2007 the number of named storms and the accumulated cyclone energy (ACE; Bell et al. 2000) were near normal (Brennan et al. 2009).

Dvorak or Dvorak-like techniques (H08; CK09; Knaff 2010; HBF10) which are also univariate empirical methods. It is quite possible that the close correspondence of both the CBE and GWE to the IBTrACS data is a reflection of the preponderance of Dvorak-type estimated winds and pressures in the best-track dataset. Both the CBE and GWE are then able to recover a form similar to that used in the original Dvorak-type estimate. What is surprising is how close both the CBE and GWE correspond to the available estimates and to each other.

For example, the CBE and GWE model curves for the 1977-2006 in the West Pacific basin (Fig. 8a) are very similar. However, TC wind speed/pressure pairs in the West Pacific basin for the 1977-2006 period have a remarkably different character than those before 1977 (Fig. 8b). The 1977-2006 data lie in a fairly close cluster about the CBE and GWE curves (Fig. 8a). The pre-1977 data exhibit much more scatter, and are not well-represented by the CBE and GWE curves determined from the 1977-2006 data (Fig. 8b). This helps explain the poor performance of the GWE used in 20CRv2 in the independent comparison period shown in Fig. 5.

These results may demonstrate a preponderance of Dvorak or Dvorak-like satellite-based TC estimates in the West Pacific in the 1977-2006 data. They may also be suggestive of an oversimplified model in the West Pacific, i.e., the assumption that all West Pacific TCs have the same wind-pressure relationship. Previous work has identified at least three different TC tracks in this region (Elsner and Liu 2003).

b. A Dvorak-free subset

To investigate the effect of the Dvorak-type estimates on the parameters calculated for the GWE and CBE models, we first consider the suggestion of H08 that westward moving TCs west of 70°W in the North Atlantic basin are relatively independent of the Dvorak technique. Aircraft reconnaissance is frequently used to observe this subset of storms that pose a potential threat to North America. We extracted from IBTrACS v03r01 data only westward-moving TCs during the period 1989 to 2009 within this western sub-basin of the North Atlantic. The choice of a 20-year period rather than the 30 years chosen for the 20CRv2 ensures good quality while still maintaining a relatively large sample size. The TCs were further restricted to those that did not make landfall as TCs and that had maximum winds greater than 17 m s^{-1} and central pressure values less than 1005 hPa. These thresholds ensure removal of extra-tropical cyclones (H08). This left us with a potentially "Dvorak-free" dataset. Parameters for the GWE (4) and CBE (1) models were then calculated.

Figure 9 shows that using a potentially Dvorak-free dataset does little to vary the previous results. All panels of Figure 9 show three curves: the North Atlantic GWE used in 20CRv2, and the GWE and CBE with parameters determined using only the Dvorak-free data subset. Also shown are wind speed and pressure values from 1989 to 2009 from four different subsets of the IBTrACS v03r01 North Atlantic datatset: storms with westward or eastward motion and storms located west or east of 70°W. Note the points in Fig. 9a constitute the "Dvorak-free" dataset. The curves are nearly identical except at speeds below about 20 m s^{-1} (where there are no data in the Dvorak-free dataset), and the data cluster about the curves in a fairly balanced fashion. Figure 10 shows the bias and root mean square error of these three models for westward-moving IBTrACS subsets, i.e., those plotted in Figs. 9a and 9b. The performance of the "Dvorak-free" GWE and CBE is almost identical. The bias of the GWE used in 20CRv2 is generally larger than those of the "Dvorak-free" models west of 70°W and smaller than them east of 70°W. Similarly, the RMS of the GWE used in 20CRv2 is equal to or slightly higher than those of the "Dvorak-free" GWE and CBE for data west of 70°W (Fig. 10c), and slightly lower for data east of 70°W in almost all categories (Fig. 10d). This is not a surprise, as the parameters for the GWE used in 20CRv2 were determined from data values spanning the basin while the other models' parameters were determined from westward moving TCs west of 70°W.

While overall RMS and bias statistics of the three models with the eastward-moving subsets are similar, the GWE used in 20CRv2 seems to outperform the others slightly in the majority of the TC categories (not shown). Those subtle differences in statistics may indicate that the parameters of the GWE used in 20CRv2 are dependent on wind speed and pressure data determined using the Dvorak technique, while the GWE and CBE parameters determined from with the "Dvorak-free" dataset are not. Alternatively, the results could reflect slightly different real-world relationships between wind speed and pressure in the various subsets of TCs in the Atlantic basin. While recent developments in multivariate wind speed/pressure relationships have focused on incorporating latitudinal variations (e.g. KZ07, CK09), there is some other evidence suggesting that longitudinal variations in wind speed/pressure relationships may exist. Velden et al. 2006 indicated that each of the 3 Australian TCWCs was using a different relationship; that JMA had modified the shape of the Dvorak (1984) relationship, and that JTWC satellite analysts applied the Dvorak technique slightly differently to each of the five basins they were responsible for. All these effectively mean that longitudinal differences were taken into consideration. Hendricks et al. (2010) extracted West Pacific and Atlantic best-track records for TCs that were at least 24 hours from land, and then for each basin assigned the records to one of four bins based on whether the storms were weakening, neutral, intensifying, or rapidly intensifying. Our analysis of the composite mean maximum winds, minimum pressures, and longitude presented in the Hendricks et al. (2010) Table 3 shows that in both basins the weakening storms are the furthest west of the four stages. The weakening storms are also the strongest (lowest minimum pressure and highest maximum winds), and have higher wind speeds for their minimum pressures than would be expected from the curves defined by the CBE and GWE parameters in Table 5.

c. Error sensitivity analysis in a perfect model context

The bias and RMS analysis in the previous sections provide some insight on systematic and random errors in the wind speed/pressure relationships and the wind speed and pressure estimates themselves. It may therefore be interesting to determine the expected effect of errors in the wind speed on the derived pressure, in the absence of any other source of errors. Such an error sensitivity analysis with pseudo errors (Monte Carlo simulation) can be used to infer the sensitivity to uncertainties in general (both systematic and random errors). The combination of the actual and expected error analyses can be used to assign observational errors for the pressure estimates when they are used in global reanalyses.

Pseudo errors were used to compare the sensitivity of the GWE and CBE models with parameters determined only from westward-moving Atlantic basin TCs west of 70°W (from Fig. 9). Wind speed values were generated with an additive error. These errors were drawn from a set of Gaussian distributions (N=10 000, 1 standard deviation ranging from 5-25 m s^{-1} in 5 m s^{-1} intervals) and were added to wind speeds ranging from 40-70 m s^{-1} in 5 m s^{-1} intervals. A small number of negative wind speeds that amounted to less than 1% of the population were transformed to positive values by multiplying them by -1.0. The lines in Fig. 11 show the standard deviation of the corresponding estimated pressure values. Slopes from the GWE (Fig. 11a) are slightly steeper than those of CBE (Fig. 11b), suggesting the central pressure values estimated from the CBE would have smaller errors than those estimated from the GWE. A similar analysis in the West Pacific basin likewise shows that the CBE (Fig. 12a) is less sensitive to wind errors than the GWE (Fig 12b). Further error sensitivity Monte Carlo simulations reveal that the CBE is expected to have smaller errors in estimated central pressure than the GWE in seven out of the nine basins (not shown).

Given the difference between the expected error of the CBE and GWE shown in Fig. 11, it is somewhat surprising that the actual RMS values in Figs. 7c,d and 10c,d are so similar for the two models. It is also surprising that the actual RMS differences in Figs. 7c,d and 10d are *smaller* than the expected errors. Only in the "Dvorak-free" subset of the Atlantic basin do we find RMS differences that are comparable to the expected error, and then for an error in wind speed of about 5 m s^{-1}. This wind speed error is more than twice the expected error from early dropsondes used in tropical cyclone reconnaissance (Hock and Franklin 1999) and about twice that assigned to 1000 hPa winds in a recent impact study (Weissmann et al. 2011), but could also include "representativeness" error. The result lends further support to the idea that many of the pressure/wind pairs have a Dvorak-type influence to which both models are related.

5. Discussion

Estimated TC minimum central pressures for 20CRv2 (and the upcoming version 3, called Sparse Input Reanalysis for Climate Applications (SIRCA)) complement existing TC pressure estimates for use in global reanalysis efforts. In order to control uncertainty, we have hypothesized that central pressures are best estimated using a univariate wind speed/pressure relationship, even at the expense of an expected smaller error from more precise multivariate wind speed/pressure relationships (e.g., KZ07, H08, CK09, HBF10). Such a dataset is not designed to augment TC reanalysis efforts such as HURDAT for many reasons, one of which is that to do so would introduce TC estimates constrained strongly towards univariate relationships. We believe that multivariate methods such as CK09/KZ07 and H08/HBF10 are more suitable for TC best track reanalysis efforts.

Recent research has developed more accurate operational TC estimates and improved the TC best-track databases through reanalysis. Such reanalysis can be expected to continue to improve the databases as issues in various estimation techniques are addressed. Knaff et al. (2010) showed that the Dvorak technique has limitations in estimating storms below 90 kt and above 125kt, and developed a quadratic bias correction equation for maximum wind with multiple inputs in the Atlantic basin. Recently, the KZ07/CZ09 algorithm has been adapted to the Advanced Dvorak Technique (Burton et al, 2010) and adopted for operational use by the Australian Bureau of Meteorology (CZ09).

As TC intensity estimation moves away from the traditional Dvorak technique, using multivariate wind speed/pressure relationships, it is prudent that future global reanalysis efforts examine their input TC estimates carefully before assimilating them. In assigning an uncertainty to a TC intensity value, global reanalysis systems need information on how that value was obtained by the best track dataset. For example, a satellite-estimated central pressure is expected to have a larger error than aircraft reconnaissance, but the RMS difference statistics shown in Figs. 7c,d and 10d do not reflect this expectation. This is likely because the underlying wind estimates are affected by the Dvorak technique. The IBTrACS dataset does not contain the metadata necessary to determine the source of the pressure values.

An additional issue for the use of TC information in global reanalyses is the inhomogeneity of the tropical cyclone historical records (Harper and Callaghan 2006; Kossin et al. 2007). For example, Black (1993) attributes inconsistent typhoon data in the Pacific basin to two different wind speed approximation methods. Kruk et al. (2009) also cite inter-agency variability as a major source of inhomogeneity and suggest that future TC reanalysis datasets provide some adjustment. Other than normalizing all non-10 minute winds to the WMO standard 10-minute average, IBTrACS has not been adjusted to achieve long-term homogeneity. The effect of introducing inhomogeneous tropical cyclone data to global scale reanalyses is unknown.

An additional homogeneity concern is the issue of undetected cyclones in the pre-satellite period. The rapid increase in the number of central pressure estimates seen in Fig. 3 shows the lack of aircraft and satellite technology before the 1950s. For example, Chang and Guo (2007) and Mann et al. (2007) show a TC undercount in the North Atlantic basin in earlier periods (see also, Landsea et al., 2010). Vecchi and Knutson (2008) estimate the expected number of Atlantic tropical cyclone missed by the pre-satellite observing system (1878-1965). Preliminary results by Truchelut and Hart (2011) suggest that their method to improve Best-Track revision efforts along with 20CRv2 would potentially lead to a more complete climatological record of global TCs and their long-term trends.

6. Conclusions

Approximately 65 000 supplemental central pressure values, estimated from IBTrACS v01r01 wind speed estimates using a univariate GWE wind speed/pressure relationship, were assimilated into the recent 20th Century Reanalysis Project version 2 (20CRv2) dataset. The parameters for the GWE were calculated for each of nine global sub-basins using all IBTrACS v01r01 wind speed and central pressure pairs from 1979 to 2007. Recent studies such as Truchelut and Hart (2011) have demonstrated several positive impacts of this effort.

The present study has investigated univariate wind speed to pressure relationships that could be used with best-track TC wind speeds to generate supplemental pressure values for future sparse input reanalysis efforts. These would include the 1850-present global reanalysis proposed by NOAA and CIRES (Sparse Input Reanalysis for Climate Applications, Compo et al. 2010) or ECMWF's planned comprehensive atmospheric reanalysis spanning the entire twentieth century (ERA-20C, Dee et al. 2011). In the investigation, North Atlantic TC central pressures from the GWE model used for 20CRv2 were compared with those from a version of the Cyclostrophic Balance Equation (CBE) that used parameters given by Brown et al. (2006). Verification against HURDAT data (1977-2006) showed similar RMS errors for both the GWE and CBE, but much smaller biases in category 4 and 5 TCs with the GWE. Global GWE-estimated central pressures, sorted by basin and Saffir-Simpson category, were compared with IBTrACS central pressure estimates from an independent time period. RMS errors tended to increase with increasing intensity and decreasing sample size, with the largest overall errors in the East and Central Pacific sub-basins. We then computed our own CBE parameters for the West Pacific and North Atlantic basins and estimated a new set of TC central pressure values. The resulting error statistics compare favorably with the similarly estimated GWE values; RMS errors are almost identical, and biases are usually smaller with the CBE.

Given information on how TC operational centers estimated their TC data, we examined whether it is possible to identify a bias in satellite-based estimates. North Atlantic TC estimates were used to illustrate the procedure of H08 for removing the systematic bias toward the Dvorak technique. New sets of parameters for both the GWE and the CBE models were calculated using wind speed/pressure pairs from only westward-moving North Atlantic TCs west of 70°W, which were presumed to have minimal Dvorak influence (H08). These "Dvorak-free" models were found to have similar bias and RMS statistics. They outperform the GWE used in 20CRv2 with the westward-moving North Atlantic TCs west of 70°W, but are outperformed by the 20CRv2 GWE with westward-moving TCs east of 70°W. This, coupled with the similarity of their curves to the 20CRv2 GWE curve, leads us to conclude that we cannot find evidence of a Dvorak *bias* in the North Atlantic IBTrACS data. This is consistent with the findings of Knaff et al. (2010) that analysts make an adjustment knowing that Dvorak biases exist in the "raw" satellite observations. Further, they found that the bias that does tend to exist in the absence of aircraft reconnaissance data varies interannually and is therefore very hard to categorize. However, we detected a discrepancy between actual and expected errors of the univariate wind speed/pressure models outside of the "Dvorak-free" area. This suggests that the Dvorak *influence* remains in the surprisingly small RMS differences between the model and IBTrACS pressure estimates.

We therefore conclude that many of the best-track TC records in IBTrACS contain estimates that were made with Dvorak or Dvorak-like univariate wind speed/pressure relationships. For an operational setting, removing this dependence before deriving either a univariate or multivariate wind speed/pressure relationship is important. For global reanalysis, there is a compelling reason to continue utilizing best-track records to create supplemental historical TC pressure records for the 20CR or similar endeavors. Despite the known limitations, we believe that including even imperfect TC estimates into global reanalysis systems may yield more realistic fields for climate research than the alternative, which is incorporating only the few TC pressure records contained in the best-track datasets.

The question remains as to which model to use. Monte Carlo simulations indicate that the CBE is expected to have a smaller random error than the GWE. This is probably because the method used to fit the parameters yields an equation in which wind speed is raised to a power less than 2. A decision on whether to select the GWE or the CBE for a given project will depend on the user's needs. If small errors are most important, the CBE should be used, as it has been for many decades. If physicality is most important, the GWE should be used, as it preserves the squared speed relationship with central pressure consistent with atmospheric dynamics. Building on the results of KZ07 and CZ09, the univariate GWE could be easily improved to incorporate latitudinal dependence by retaining the Coriolis parameter f or binning the basin by latitudes

(Landsea 2004), thereby tuning the GWE further for each sub-basin. These modifications may result in a greater accuracy while still maintaining a model with parsimonious inputs. Testing this hypothesis is the subject on ongoing work.

With these and other developments, we anticipate that improvements in the representation of tropical cyclones will continue in future global reanalysis efforts.

Acknowledgments.

We would like to thank G. Holland (NCAR) for providing us the early manuscript of the Holland (2008) model when this project started. We would like to thank M. Kruk, K. Knapp, and D. Levinson (NOAA/NCDC) for kindly providing us the IBTrACS data and providing suggestions on an earlier version of the manuscript. We thank P. Sardeshmukh (CIRES Climate Diagnostics Center and NOAA/ESRL/PSD) and J. Whitaker (NOAA) for their input and assistance. We thank E. Araujo-Pradere (CIRES and NOAA/SPWC) and C. McColl (CIRES Climate Diagnostics Center and NOAA/ESRL/PSD) for reviewing an earlier version of the manuscript. C. Penland (NOAA) was an inspiration for our error analysis. We appreciate consultation on various aspects of Atlantic hurricanes provided by C. Landsea and S. Aberson (NOAA/AOML) and useful discussions with C. Wilson (NOAA/ESRL/GMD) and S. Tulich (CIRES and NOAA/ESRL/PSD). We appreciate the insights on operational TC procedures provided by A. Burton (Australian Bureau of Meteorology) and J. Courtney (Bureau of Meteorology Training Centre/Perth). A high resolution land-sea mask was provided by Jon Eischeid (NOAA/ESRL/PSD). The Twentieth Century Reanalysis Project used resources of the National Energy Research Scientific Computing Center and of the Oak Ridge Leadership Computing Facility at Oak Ridge National Laboratory, which are supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and Contract No. DE-AC05-00OR22725, respectively. Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. This work was supported by the NOAA Climate Program Office.

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List of Figures

FIG.1. The mean sea level pressure field at 06 UTC on 14 August 1958 during Hurricane Cleo, as depicted in four different reanalysis data sets: a) 20CRv1, b) 20CRv2, c) NCEP-NCAR, and d) ERA-40. Note that IBTrACS (v01r01) does not contain a pressure estimate for this storm at any time prior to 06 UTC, and at 06 UTC it contains a wind estimate but no central pressure estimate for this storm. Contour interval is 4 hPa.

FIG. 2. Locations of IBTrACS v01r01 central pressures during the year 2000 for nine different sub-basins. The main-basin/sub-basin abbreviation combinations that have been adapted from IBTrACS are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Australia), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

FIG. 3. Total number of estimated TC central pressure values from IBTrACS v01r01 and 20CRv2 in ten-year intervals (1851-2007). The 20CRv2 central pressure values were estimated from IBTrACS wind speeds using the GWE (4) whenever estimated central pressures were not available in IBTrACS. Note that less than 10 years of data are available for the final decade plotted.

FIG. 4. (a) Mean bias and (b) RMS error as a function of Saffir-Simpson category for TC central pressures estimated with two different empirical wind speed/pressure relationships: a form of the cyclostrophic balance equation (CBE, see (1)) with

parameters from Brown et al. (2006), and a form of the gradient wind equation (GWE, see (4)) with parameters fit using 1977-2006 HURDAT estimates. HURDAT central pressure estimates from 1977-2006 are used as verification. The total number of sample points is given in Table 2 Bias and RMS for the GWE are determined from three-year jack-knifing. Since the CBE parameters are taken from Brown et al. (2006), no jack-knifing is used in the calculation of the CBE error statistics.

FIG. 5. RMS error as a function of TC intensity for GWE-derived central pressures compared to IBTrACS central pressure estimates. GWE parameters were estimated separately for each of the nine sub-basins defined in Fig. 2 using IBTrACS wind speed and pressure values from the independent period 1979-2007. Statistics were calculated over the period 1958 to 1978, and are shown only for sub-basins and categories with more than 30 values. (Note that NI is included in the Overall category with only 18 total data points during the 1958 to 1978 period). The total number of sample points used to estimate the parameters is given in Table 3.

FIG. 6. Spatial distribution of TC central pressures during the 1960s (left) and 1990s (right). Locations are shown for TC central pressures (a,c) already available in IBTrACS v01r01 and (b,d) determined for 20CRv2 from IBTrACS wind estimates using the GWE (4).

FIG. 7. Error statistics of estimated pressures determined from two wind speed/pressure relationships, shown as a function of tropical cyclone intensity and based on IBTrACS

data (1977-2006). Shown are (a,b) mean bias and (c,d) RMS error for the (a,c) West Pacific, (b,d) North Atlantic. The total number of sample points is given in Table 5, together with the CBE and GWE parameters. Both bias and RMS error for the GWE and CBE are the result of cross-validation using three year jack-knifing.

FIG. 8. Scatter plot of IBTrACS v01r01 wind-speed and central pressure estimates compared to the GWE (solid line) and CBE (dashed line) for the Western Pacific. Data are from the period (a) 1977-2006 and (b) 1958-1976, respectively. The GWE in both panels is based on parameters determined using 29 294 IBTrACS v01r01 data points from 1979-2007, shown as open circles in (a). The IBTrACS wind-speed and central pressure estimates in the lower panel are entirely independent from the data values used to derive the GWE parameters.

FIG. 9. Comparison of wind speed-pressure data stratified by the region of the North Atlantic and direction of storm movement. Curves show the Gradient Wind Equation (GWE) used to estimate Atlantic Basin TC central pressures for 20CRv2 (dotted line) and for the GWE (solid line) and CBE (dashed line) whose parameters were determined using only the data plotted in Panel a, i.e. the westward-moving TCs west of 70°W from IBTrACS v03r01 (1989-2009). Plotted as open circles are 1989 to 2009 data from IBTrACS v03r01: a) 828 data points from westward-moving TCs west of 70°W, b) 1753 data points from westward-moving TCs east of 70°W, c) 459 data points from eastward-moving TCs west of 70°W, and d) 1590 data points from eastward-moving TCs east of 70°W.

FIG. 10. Mean bias of the 1989-2009 wind speed/pressure relationship approximations examined in Fig. 9 for North Atlantic TCs (a) west of 70°W (b) and east of 70°W, together with the corresponding RMS error (c) west of 70°W and (d) east of 70°W. The total number of sample points is in Table 6.

FIG. 11. Sensitivity of a) GWE and b) CBE central pressures to pseudo errors in wind speed. The GWE and CBE parameters were calculated empirically from the westward-moving TCs from west of 70°W in the North Atlantic basin. A set of uncertainties in winds ranging from 5 to 25 m s^{-1} in 5 m s^{-1} intervals were applied to a set of wind speeds (40-70 m s^{-1} in 5 m s^{-1} intervals). The one standard deviation GWE and CBE model responses in pressure are plotted along the y-axis.

FIG. 12. Sensitivity of a) GWE and b) CBE central pressures to pseudo errors in wind speed. The GWE and CBE parameters were calculated empirically from the TCs in the West Pacific basin. A set of uncertainties in winds ranging from 5 to 25 m s^{-1} in 5 m s^{-1} intervals were applied to a set of wind speeds (40-70 m s^{-1} in 5 m s^{-1} intervals). The one standard deviation GWE and CBE model responses in pressure (hPa) are plotted along the y-axis.

TABLE 1. Total number of IBTrACS v01r01 TC estimates (1851-2007) in each basin, together with counts of the number of central pressure estimates available in the IBTrACS dataset and the number estimated from IBTrACS wind-only reports for 20CR. Basin abbreviations are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacific), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	Number of IBTrACS TC Estimates by Type				
Basin	**Pressure + Wind**	**Pressure Only**	**Subtotal**	**Wind Only**	**Total**
EPCP	1141	269	1410	2361	3771
EPEP	7575	0	7575	11 013	18 588
NA	13 367	0	13 367	25 997	39 364
NI	2212	42	2254	2379	4633
SI	10 604	190	10 794	9194	19 988
SIWA	9068	1896	10 964	1483	12 447
SPEA	4848	1767	6615	994	7609
SPSP	8737	266	9003	2923	11 926
WP	56 549	8711	65 260	7857	73 117
Total	114 101	13 141	127 242	64 201	191 443

TABLE 2. Total number of 1977-2006 HURDAT TC wind speed estimates as a function of Saffir-Simpson category, together with the speed range associated with each category.

Saffir Simpson Category	Wind speed (kt)	Wind speed (m s^{-1})	Number of Estimates
Sub-Hurricane Cyclones	< 64	< 32.9	5696
Category 1	64 – 82	32.9 - 42.2	1430
Category 2	83 – 95	42.7 - 48.9	557
Category 3	96 – 113	49.4 - 58.4	412
Category 4	114 – 135	58.6 - 69.5	196
Category 5	> 135	> 69.5	65
Overall			8356

TABLE 3. Gradient wind equation (GWE) parameters used to estimate central pressures for the 20CRv2. The parameters were calculated for each sub-basin using the given (# obs) IBTrACS v01r01 pairs of V and P_c over the period 1979-2007, and are valid for peak 10-minute average wind speeds. Basin abbreviations are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacific), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	EPCP	**EPEP**	**NA**	**NI**	**SI**	**SIWA**	**SPEA**	**SPSP**	**WP**
P_{ref}	1017.74	1016.17	1018.42	1001.87	1014.38	1016.31	1014.55	1013.53	1012.85
α	0.533 429	0.529 944	0.734 988	0.135 548	0.919 901	1.238 93	1.014 78	0.933 561	0.653 169
β	0.015 144 9	0.015 567 6	0.012 598 2	0.022 883 4	0.013 062 8	0.007 411 85	0.010 073 1	0.012 698 6	0.017 715 6
# obs	1018	7442	10 595	2192	9864	5793	2850	6559	27 957

TABLE 4. Total number of IBTrACS v01r01 TC estimates from 1958-1978 in each bas together with counts of the number of central pressure estimates available in IBTrACS dataset and the number estimated from IBTrACS wind-only reports. Ba abbreviations are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (No Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Pacifi SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

	Number of IBTrACS TC Estimates by Type				
Basin	**Pressure + Wind**	**Pressure Only**	**Subtotal**	**Wind Only**	**Total**
EPCP	92	105	197	820	1017
EPEP	131	0	131	5579	5710
NA	2259	0	2259	3886	6145
NI	18	20	38	436	474
SI	740	69	809	5992	6801
SIWA	3173	580	3753	182	3935
SPEA	1970	253	2223	351	2574
SPSP	2150	92	2242	1775	4017
WP	21 612	4685	26 297	587	26 884
Total	32 145	5804	37 949	19 608	57 557

TABLE 5. Gradient wind equation (GWE) and cyclostrophic balance equation (CBE) coefficients used to estimate central pressures in the West Pacific (WP) and North Atlantic (NA) basins. The coefficients were calculated for each sub-basin using all IBTrACS v01r01 (V, P_c) records, 1977-2006, and are valid for peak 10-minute average wind speeds in units of knots.

	NA	**WP**
GWE parameters		
P_{ref}	1018.29	1012.75
α	0.714 043	0.653 342
β	0.012 928 3	0.017 724 7
CBE parameters		
c	3.121 89	3.393 19
P_{ref}	1015.41	1009.87
k	0.663 389	0.624 675
Number of records	10 482	29 294

Table 6. Number of TC wind speed estimates in IBTrACS v01r01 from 1977-2006 in the West Pacific (WP) and North Atlantic (NA) basins as a function of Saffir-Simpson category.

	WP	**NA**
Sub-Hurricane Cyclones	22 832	8588
Category 1	3690	1066
Category 2	1524	356
Category 3	1037	355
Category 4	206	106
Category 5	5	11
Overall	29 294	10 482

Table 7. Number of westward-moving TCs in IBTrACS v03r01 from 1989-2009 as a function of Saffir-Simpson category for two different regions of the North Atlantic basin.

	West of 70°W	**East of 70°W**
Sub-Hurricane Cyclones	451	1116
Category 1	129	296
Category 2	89	127
Category 3	962	185
Category 4	59	29
Category 5	4	0
Overall	828	1753

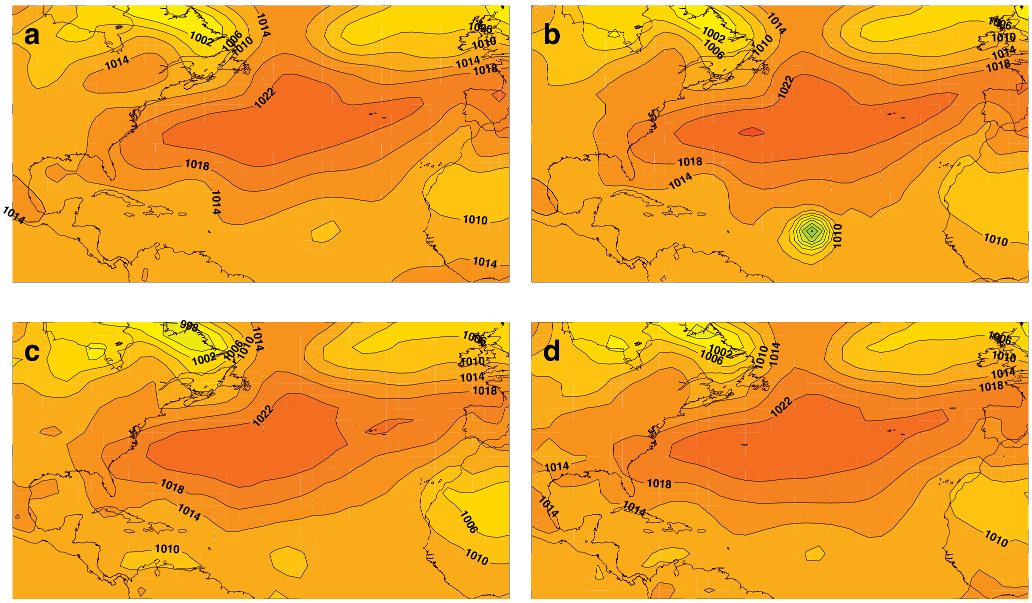

FIG.1. The mean sea level pressure field at 06 UTC on 14 August 1958 during Hurricane Cleo, as depicted in four different reanalysis data sets: a) 20CRv1, b) 20CRv2, c) NCEP-NCAR, and d) ERA-40. Note that IBTrACS (v01r01) does not contain a pressure estimate for this storm at any time prior to 06 UTC, and at 06 UTC it contains a wind estimate but no central pressure estimate for this storm. Contour interval is 4 hPa.

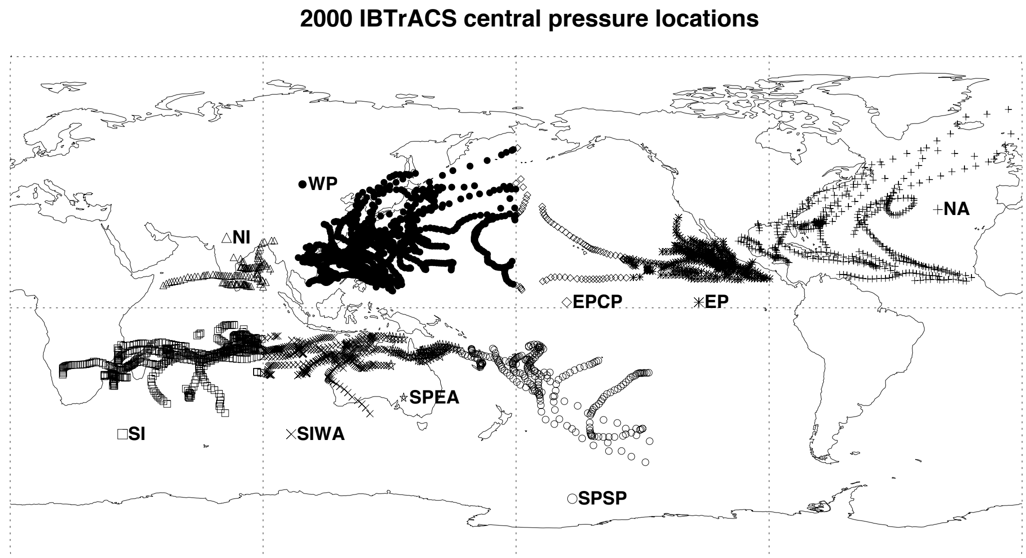

FIG. 2. Locations of IBTrACS v01r01 central pressures during the year 2000 for nine different sub-basins. The main-basin/sub-basin abbreviation combinations that have been adapted from IBTrACS are: EPCP (East Pacific/Central Pacific), EPEP (East Pacific), NA (North Atlantic), NI (North Indian), SI (South Indian), SIWA, (South Indian/West Australia), SPEA (South Pacific/East Australia), SPSP (South Pacific), WP (West Pacific).

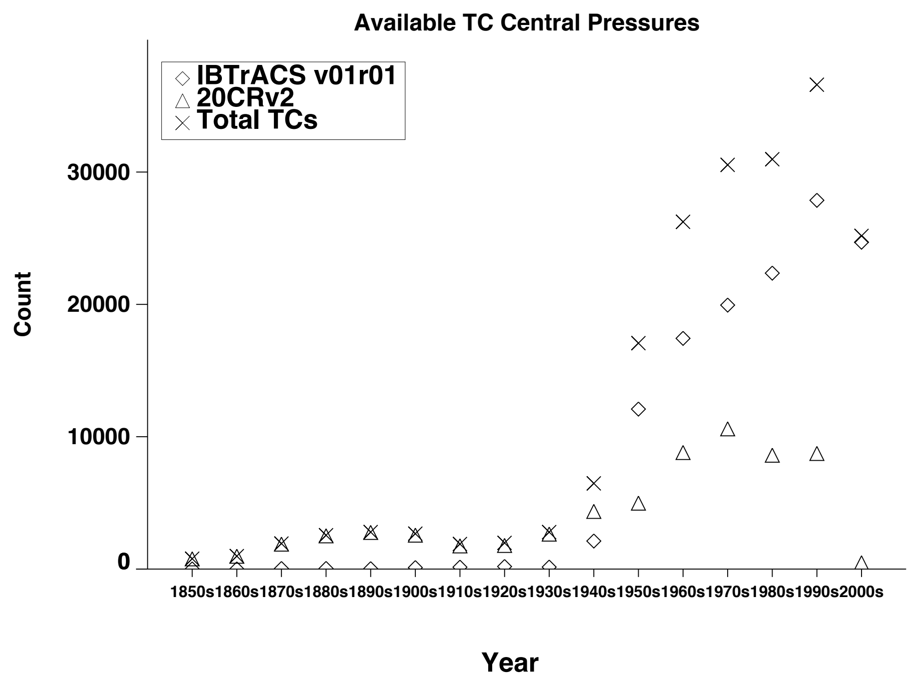

FIG. 3. Total number of estimated TC central pressure values from IBTrACS v01r01 and 20CRv2 in ten-year intervals (1851-2007). The 20CRv2 central pressure values were estimated from IBTrACS wind speeds using the GWE (4) whenever central pressure values were not available directly from IBTrACS. Note that less than 10 years of data are available for the final decade plotted.

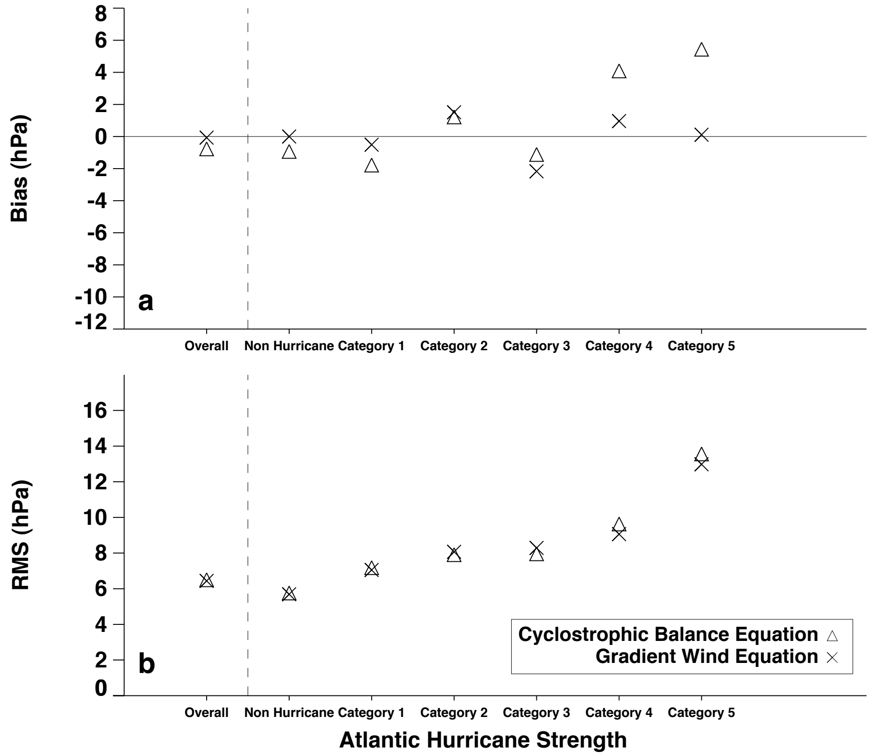

FIG. 4 (a) Mean bias and (b) RMS error as a function of Saffir-Simpson category for TC central pressures estimated with two different empirical wind speed/pressure relationships: a form of the cyclostrophic balance equation (CBE, see (1)) with parameters from Brown et al. (2006), and a form of the gradient wind equation (GWE, see (4)) with parameters fit using 1977-2006 HURDAT estimates. HURDAT central pressure estimates from 1977-2006 are used as verification. The total number of sample points is given in Table 2 Bias and RMS for the GWE are determined from three-year jack-knifing. Since the CBE parameters are taken from Brown et al. (2006), no jack-knifing is used in the calculation of the CBE error statistics.

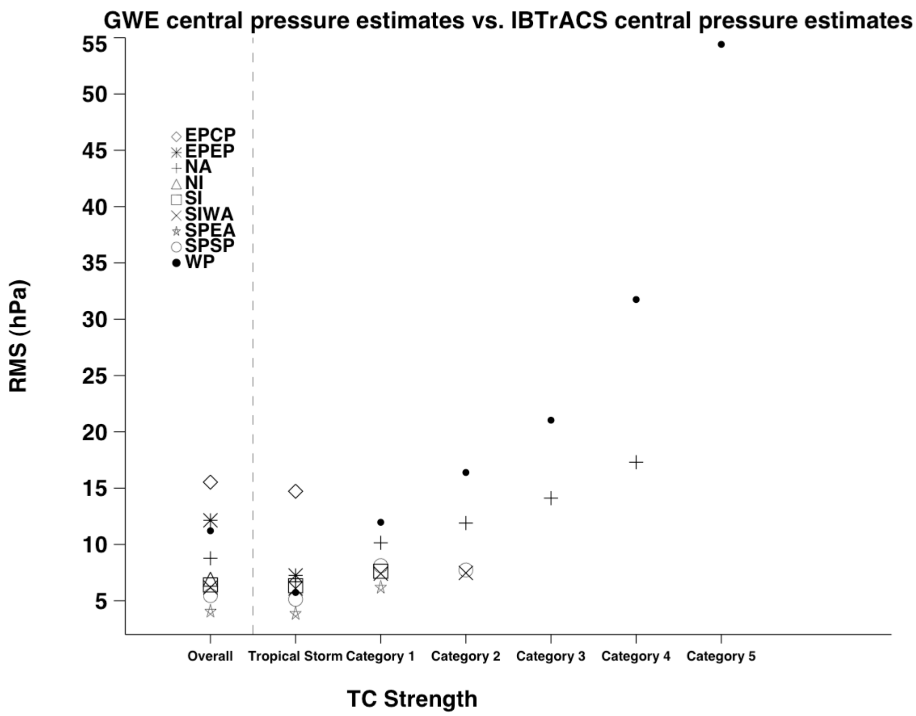

FIG. 5. RMS error as a function of TC intensity for GWE-derived central pressures compared to IBTrACS central pressure estimates. GWE parameters were estimated separately for each of the nine sub-basins defined in Fig. 2 using IBTrACS wind speed and pressure values from the independent period 1979-2007. Statistics were calculated over the period 1958 to 1978, and are shown only for sub-basins and categories with more than 30 values. (Note that NI is included in the Overall category with only 18 total data points during the 1958 to 1978 period). The total number of sample points used to estimate the parameters is given in Table 3.

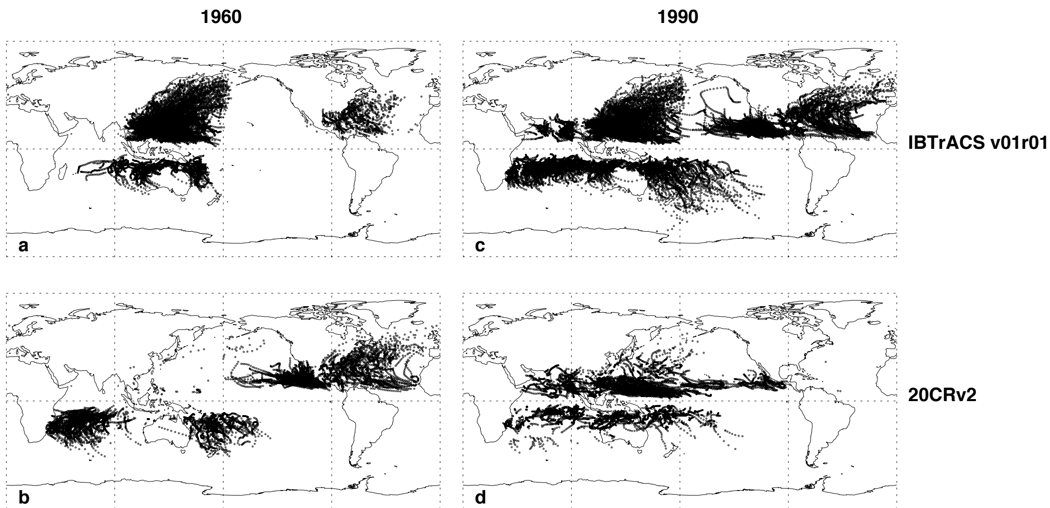

FIG. 6. Spatial distribution of TC central pressures during the 1960s (left) and 1990s (right). Locations are shown for TC central pressures (a,c) already available in IBTrACS v01r01 and (b,d) determined for 20CRv2 from IBTrACS wind estimates using the GWE (4).

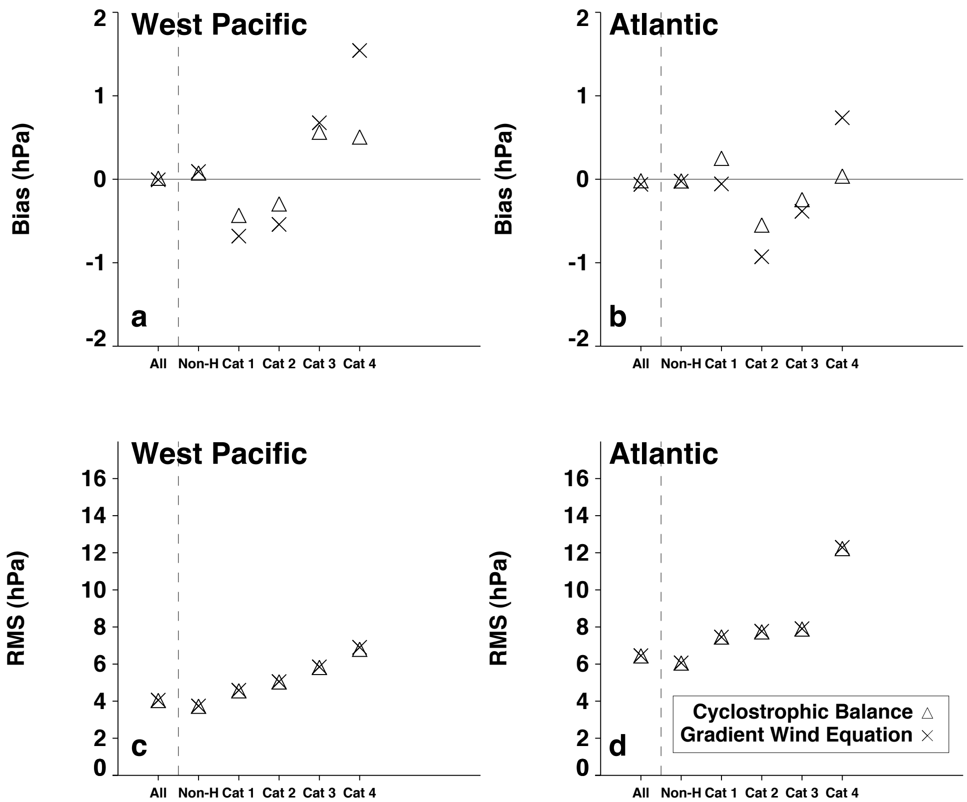

FIG. 7. Error statistics of estimated pressures determined from two wind speed/pressure relationships, shown as a function of tropical cyclone intensity and based on IBTrACS data (1977-2006). Shown are (a,b) mean bias and (c,d) RMS error for the (a,c) West Pacific, (b,d) North Atlantic. The total number of sample points is given in Table 5, together with the CBE and GWE parameters. Both bias and RMS error for the GWE and CBE are the result of cross-validation using three year jack-knifing.

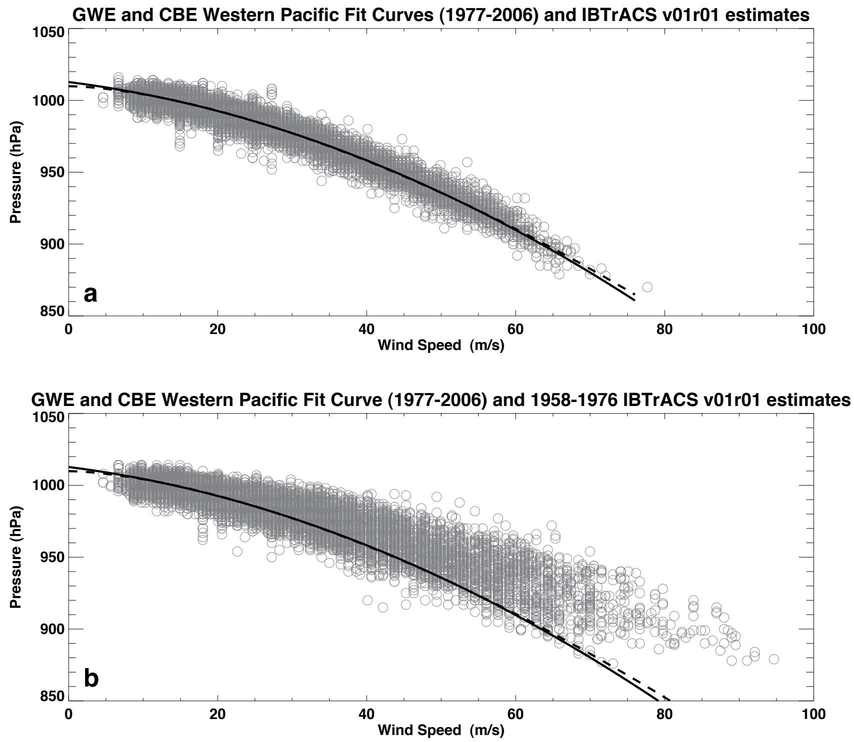

FIG. 8. Scatter plot of IBTrACS v01r01 wind-speed and central pressure estimates compared to the GWE (solid line) and CBE (dashed line) for the Western Pacific. Data are from the period (a) 1977-2006 and (b) 1958-1976, respectively. The GWE in both panels is based on parameters determined using 29 294 IBTrACS v01r01 data points from 1979-2007, shown as open circles in (a). The IBTrACS wind-speed and central pressure estimates in the lower panel are entirely independent from the data values used to derive the GWE parameters.

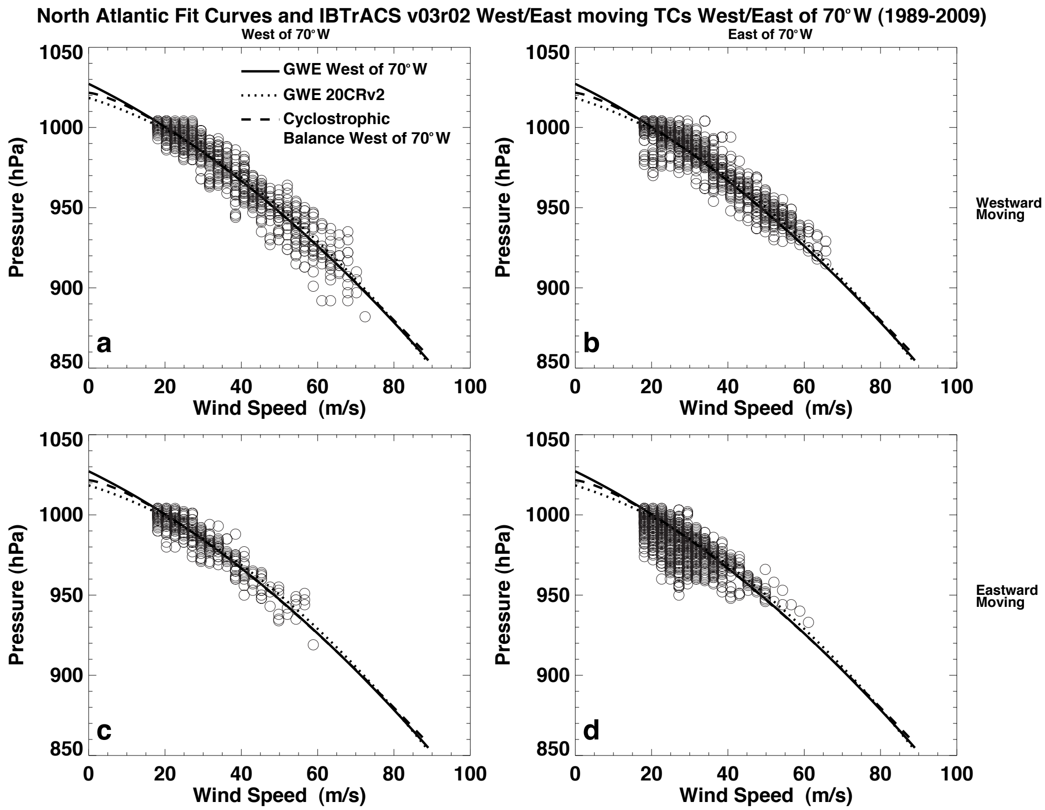

FIG. 9. Comparison of wind speed-pressure data stratified by the region of the North Atlantic and direction of storm movement. Curves show the Gradient Wind Equation (GWE) used to estimate Atlantic Basin TC central pressures for 20CRv2 (dotted line) and for the GWE (solid line) and CBE (dashed line) whose parameters were determined using only the data plotted in Panel a, i.e. the westward-moving TCs west of 70°W from IBTrACS v03r01 (1989-2009). Plotted as open circles are 1989 to 2009 data from IBTrACS v03r01: a) 828 data points from westward-moving TCs west of 70°W, b) 1753 data points from westward-moving TCs east of 70°W, c) 459 data points from eastward-moving TCs west of 70°W, and d) 1590 data points from eastward-moving TCs east of 70°W.

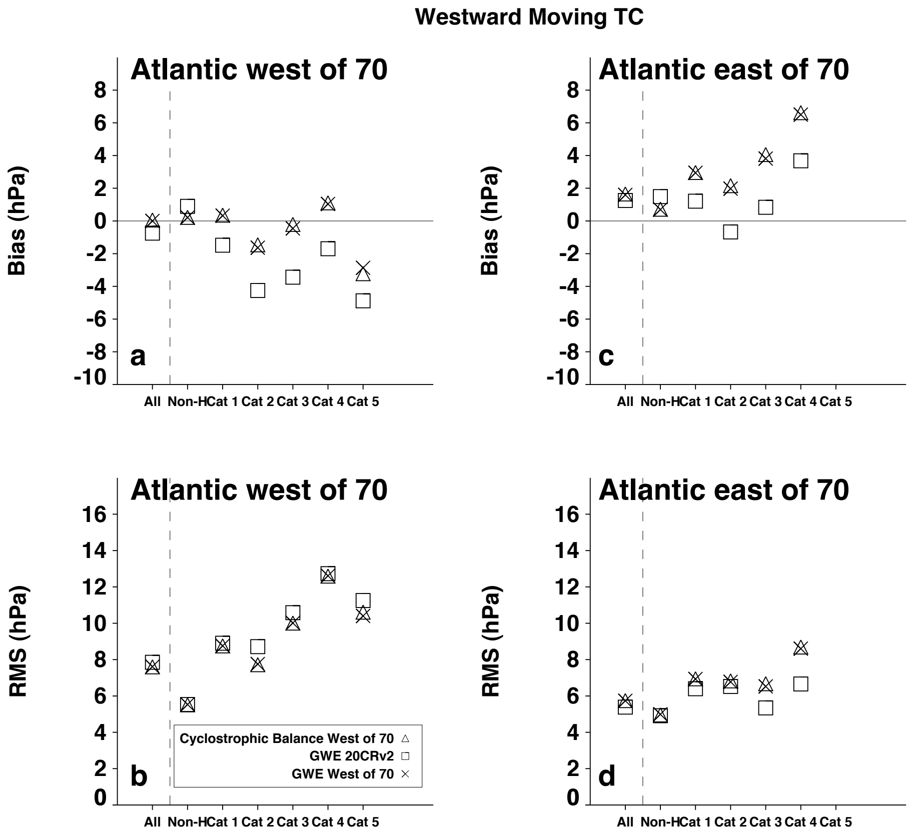

FIG. 10. Mean bias of the 1989-2009 wind speed/pressure relationship approximations examined in Fig. 9 for North Atlantic TCs (a) west of 70°W (b) and east of 70°W, together with the corresponding RMS error (c) west of 70°W and (d) east of 70°W. The total number of sample points is in Table 6.

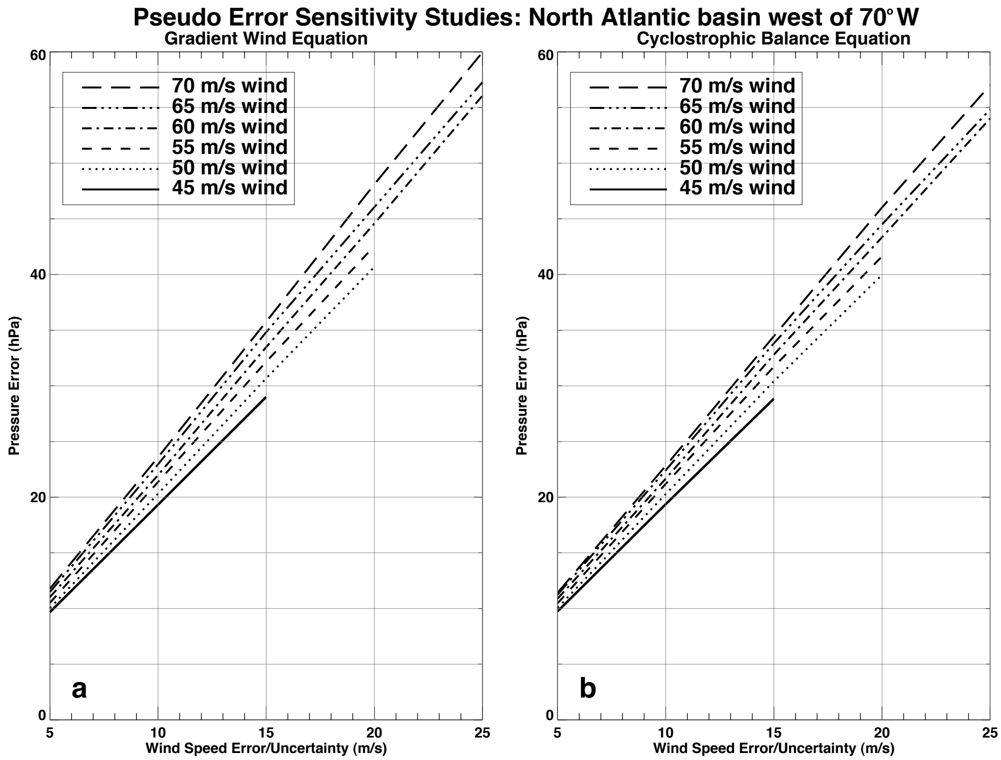

FIG. 11. Sensitivity of a) GWE and b) CBE central pressures to pseudo errors in wind speed. The GWE and CBE parameters were calculated empirically from the westward-moving TCs from west of 70°W in the North Atlantic basin. A set of uncertainties in winds ranging from 5 to 25 m s^{-1} in 5 m s^{-1} intervals were applied to a set of wind speeds (40-70 m s^{-1} in 5 m s^{-1} intervals). The one standard deviation GWE and CBE model responses in pressure are plotted along the y-axis.

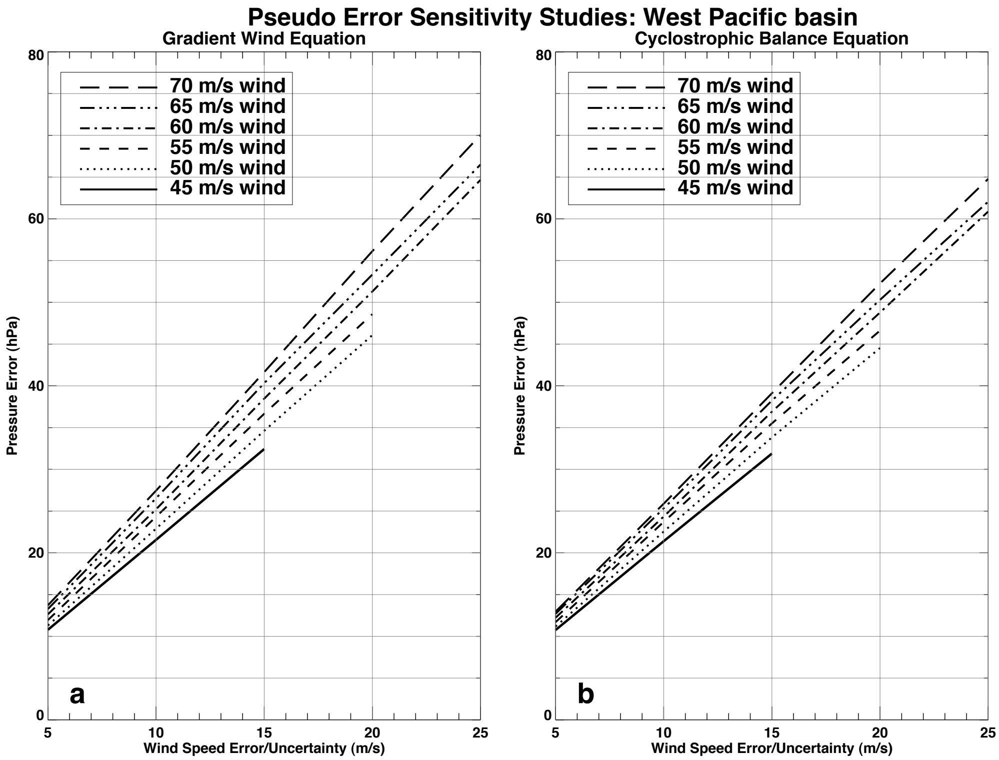

FIG. 12. Sensitivity of a) GWE and b) CBE central pressures to pseudo errors in wind speed. The GWE and CBE parameters were calculated empirically from the TCs in the West Pacific basin. A set of uncertainties in winds ranging from 5 to 25 m s^{-1} in 5 m s^{-1} intervals were applied to a set of wind speeds (40-70 m s^{-1} in 5 m s^{-1} intervals). The one standard deviation GWE and CBE model responses in pressure (hPa) are plotted along the y-axis.